Optimum Sizing and Economic Analysis of Standalone PV System with a Small Size Grinding Mill

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Abstract

This work presents the results of the characterization of a standalone photo-voltaic system for the electrification of a household located in rural area in the western region of Cameroon: Nziih-Bafou in Dschang (5.35°N, 10.05°E and 1900 m). In order to cope with the maintenance charges and reduce the in- vestment cost, a small mill was added to the appliances of the household for income generation. The assessment of the energy demand was made by tak- ing into account the reactive energy due to the heavy consumption of energy by the mill's motor, especially during ignition. The sizing of all the system's components was carried out with the prospect of determining an optimum design in accordance with daily electricity demand, site irradiance profile and climatic conditions. In this context, tilt angles applicable to the PV structure and that allow to receive the maximum irradiance as a function of the periods of the year were determined using the Hay model. This approach provides the system with incident irradiance greater than or at the limit equal to that re- ceived by a horizontal surface on the same site compared to the case of a sin-gle tilt angle where the irradiance on the inclined plane is often lower than that on the horizontal. The economic analysis of the PV system showed an initial cost of $4448 and the Life Cost Cycle amounted to $24,495. This amount corresponds to a present cost per kilowatt hour of $0.44. The Net Present Value (NPV) of the project ($7793) over its lifetime (20 years) shows a pay-back period of less than 4 years.

Keywords

Standalone Photovoltaic System, Optimization, Hay Model, Reactive Energy, Life Cycle Cost, Net Present Value

1. Introduction

Solar energy considered to be inexhaustible with regard to its potential compared to the energy needs of humanity varies according to the geographical location, the position of the sun, the orientation and the inclination of the collector. In Africa, this truly abundant energy is proving to be a major alternative to in- creasing demand due to gradual modernization of industrial processes and espe-cially the growing population [1]. Although access has been slowly rising, more than 600 million people in Africa live without electricity, including more than 80 percent of those residing in rural areas [2]. With a rate of access to electricity of barely 21% in rural areas in 2017 [3], Cameroon is struggling to meet the

elec-tricity needs of its households. In addition, problems such as the obsolescence of energy transport equipments often causing load shedding, numerous complaints about billing and quality of service, slow interventions and many other draw- backs punctuate this low access rate.

Faced with this situation which seems to be common in many African coun- tries [4], researchers are increasingly proposing the decentralized electrification solution on isolated sites and in rural areas in particular using the photovoltaic (PV) technology. In fact, Stojanovski *et al*. [5] through a survey that tracked ap- proximately 500 early adopters of solar home systems (SHS) in two off-grid mar- kets in Africa found that SHS were associated with large reductions in the use of

kerosene and to a lesser extent, the use of small disposable batteries also de- creased. In order to guarantee stable and accessible energy for the populations, Sakiliba *et al*. [6] proposed in Gambia a fixed tilt angle domestic PV system with a cost price per kWh lower than the unit price of electricity in the country. How-ever, such a generator would not have the capacity to produce using the maxi- mum radiation potential throughout the year. Kumar *et al*. [7] in view to im- prove the performance of PV systems maximized the incident energy received by solar modules by using variable optimum tilt angles according to the seasons of the year. One of the most important aspects of the standalone PV systems be- sides its reliability [8] [9] is the search for a good compromise between energy needs and the capacity to bear the installation cost which is high compared to the financial means of the populations in rural areas.

The present work in order to promote access to electricity studies the opti- mum PV sizing for a rural household in Nziih-Bafou village in the West region of Cameroon. This site was chosen for the strong economic capacities of the area which is a real commercial hub where several income-generating activities are developed. However, although connected to electrical power network, people face frequent power outage that causes significant losses in their activities. Ir- radiance on horizontal plane is also important with an annual average of 5.45 kWh/m^2/day [10]. The peculiarity of the household taken into account here is to be equipped with a food grinding mill because agriculture is the primary activity in the area. The main objective of this paper is to design for this household an autonomous, efficient PV system that can guarantee its energy independence

while contributing to income generation. This sizing is done with an optimiza- tion perspective both in the selection of equipments, the inclination of panels as the choice of electrical topology to allow the proper functioning of the PV sta- tion and to ensure a reasonable payback time.

The rest of the paper is organized as follows. Section 2 discusses the site solar potential and the household energy demand. The methodology for optimal siz- ing is presented in

Section 3. Section 4 deals with the economic and environ- mental analysis of the station. Finally, Section 5 presents the results and discusses their usefulness. The major findings of the study are summarized in Section 6.

2. Solar Potential and Energy Demand of the Household

Figure 1 shows the monthly profile of average solar irradiation at Nziih-Bafou site (10˚05'N, 5˚35'E and 1900 m) for a period of one year. These values are de- rived from Photovoltaic Geographical Information System (PVGIS) for the year 2016. PVGIS is the official site of the European Union which provides access to data on solar irradiation on horizontal plane, ambient temperature and tools for performance assessment of photovoltaic systems. The satellite data used to esti- mate the solar radiation are obtained from METEOSAT satellites covering Eu- rope, Africa and most of Asia. The site produces an image per hour for a given station from January to December, which makes it possible to generate averages on a desired time scale (PVGIS, 2020). **Figure 1** also compares these data to those received in the same locality by a flat inclined surface with tilt angle β equals to the latitude of the site ($\beta = 5˚35'$).

It can be observed that the single tilt angle is not always appropriate because there are periods of the year where the irradiance on the inclined plane is less than the horizontal as demonstrated by Akana and Kum [11].

The average household which is used in this study was described following a survey based on Simple Random Sampling in the locality and it is therefore equipped with appliances that are generally present in the area. **Table 1** summa- rizes these devices, their powers and the operating time for a day. In addition, the household has a grinding mill which consumes significant reactive energy,
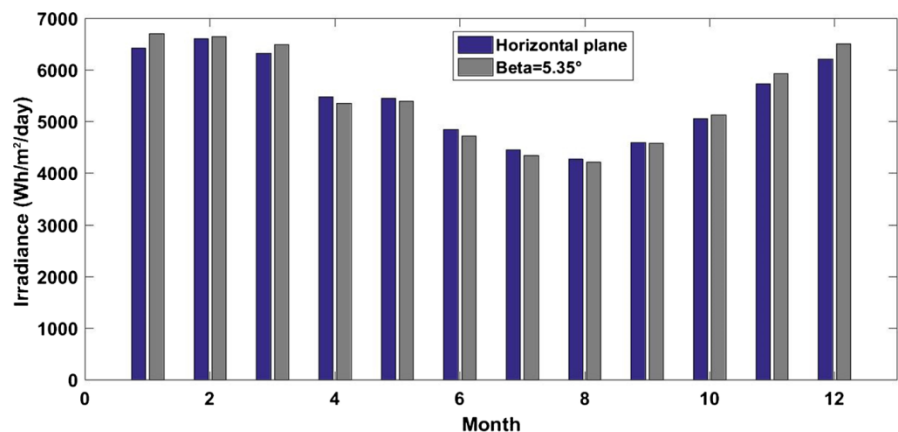

Figure 1. Sunshine on a horizontal plane (PVGIS, 2020) and for $\beta = 5˚35'$.

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Table 1. Daily power demand of the household.

Electrical Load	N° of Operating Units hours		Active power	Power factor	Reactive power	Apparent power	Energy per day
		per day	(W)	(cccccc φ)	(VAR)	(VA)	(VAh/j)
TV	1	**5**	100	0.8	75	125	625
TV Decoder	1	5	17	0.95	5.58	17.89	89.45
LED Lamps	7	7	70	0.95	23	73.68	515.76
Refrigerator	1	16	150	0.8	112.5	187.5	3000
HiFi	1	4	35	0.8	26.25	43.75	175
Iron	1	0.5	1500	1	0	1500	750
Phone Charg	4	5	20	0.95	6.57	21	10

er						.05	5.25
Mill	1	3	750	0.8	562.5	937.5	2812.5
Lapto p	1	2	65	0.8	48.75	81.25	162.5
Tot al							8235.46

Table 2. Characteristics of the mill motor.

Type	Voltage	Rotations per minute	Power	Starting Current	Duty Current	Frequency
ML 802-4	220 V	1410	750 W	30 A	4.75 A	50 Hz

especially during ignition. Daily needs are then evaluated and considered con- stant throughout the year.

The characteristics of the mill's motor are as shown in **Table 2**.

3. Design Optimization

In order to guarantee optimal operation of the station, several factors are taken into account in the design.

Optimization through Recoverable Solar Energy

The position of the photovoltaic modules relative to the sun directly influences their energy

production. It is therefore very important to appropriately install the panels so as to use them to the maximum of their possibilities. In this con- text, knowledge of the solar radiation received by an inclined surface is necessary for most applications concerning ground-based solar systems. Here we use Hay's anisotropic model [12] and evaluate the irradiation on a monthly time scale ac-cording to the method described by Akana and Kum [11] as

$$G_\beta = \left[\cos\theta_i \frac{G_b}{\cos\theta_z} + 0.5 \frac{G_d}{\cos\theta_z} \left(\frac{\cos\theta_i}{\cos\theta_z} \frac{G_b}{G_0} + (1 - \cos\beta) \left(1 - \frac{G_b}{G_0} \right) \right) \right] \quad \frac{\cos\theta_i}{2} \qquad G_\beta = G_b \tag{1}$$

where G_b

and G_d

are respectively direct and diffuse radiations on a horizon-tal surface (W/m^2). ρ is the surface albedo, G the total irradiance on horizon-tal plane(W/m^2), G_β the total irradiance on tilted surface and G_0 the solar constant. With

$$\cos\theta_i = \cos\delta \cdot \cos\theta_z + \sin\delta \cdot \sin\theta_z \cdot \cos A$$
$$\cos\theta_z = \cos\delta \cdot \sin\phi + \cos\delta \cdot \cos\phi \cdot \cos\omega$$

$$\tag{2}$$
$$\tag{3}$$

where θ_z is the solar zenithal angle, δ the declination, ϕ the latitude of the site, ω the hourly angle and A the azimuth.

Sizing and Design Technology

The optimal and harmonious functioning of a photovoltaic installation requires efficient sizing and a judicious choice of the essential elements (**Figure 3**) that make up the generator.

Photovoltaic Field
The peak power (P_p) of the PV field expressed in Watt peak (W_p) is by definition the power it

delivers under a solar radiation of 1000 W/m^2. It strongly depends on the irradiation of the site and is obtained from the following equation

$$P_p = \frac{E_{Demand}}{PR \cdot I_r} \left(1 \, kW \, m^2 \right) \tag{4}$$

E_{Demand} is the daily energy demand of the household (kWh/day) and I_r the

average daily irradiation (kWh/m^2/day) during the worst month.

PR is the de performance ratio. In the case of this installation, the modules are to be placed close to the ground to allow good ventilation of the photovoltaic field. In addition, the charge regulator is MPPT technology. We will then use $PR = 0.75$.

The number of panels in series (N_{PS}) is calculated by

$$N_{PS} = \frac{V_G}{V_P} \tag{5}$$

where V_G s the voltage across the photovoltaic generator, V_P

the rated vol-
tage of PV panel.

Similarly, the number of branches in parallel (N_{PP}) is calculated as follows

$$N_{PP} = \frac{P_p}{P_m} \cdot \frac{1}{N_{PS}} \tag{6}$$

where P_m is the peak power of PV module (W_p).

The total number N of panels to be installed is given by

$$N = N_{PS} \cdot N_{PP} \tag{7}$$

We deduce the total surface

A_T occupied by the panels

$A_T \square A_P \square N8)$

where A_P

per day

is the area of a PV panel and the energy produced by the PV field

daily $\square P_p \square N_p$

where N_p

$E_{\text{daily}} \square P_p \square N_p$

is the daily duration of Peak sunshine (hours).

(9)

Sizing of the Battery Bank

The lead-acid battery is the most common form of electrical energy storage due to an established manufacturing base, therefore a relatively low cost and wide availability. The storage capacity C_B (A·h) of the battery bank is given by

$$C_B \square E_{\text{Demand}} \square n$$

$$\square_{bat} \square_i \square_q \square \text{DOD} \square V(10)$$

With n the number of days of autonomy, DOD the maximum depth of dis-

charge (in %). $\square_{bat}, \square_i$

and $\square_q$

are the efficiencies of the battery, the inverter
and the charge controller respectively. V is Battery bank voltage (Volts).
The number of batteries in series is determined by

And in parallel we have

$B_S \square$

PV Field Voltage Battery Rated Voltage

(11)

$$B_p \square \frac{\text{Total Storage Capacity } C_B \square A \square h\square}{\text{Battery Rated Capacity} \square A \square h\square}$$

(12)

We deduce the total number of batteries for the system by

$$B \square B_p \square B_s$$

13)

Charge Controller and Inverter

The nominal input voltage of the charge controller is equal to that of the photo-voltaic field which in this case has been taken equal to 48 V. The input current (I_e) is the maximum duty current that the modules are capable of delivering at a given moment. This current is obtained by the product of the short-circuit cur- rent of a module (Icc) by the number of branches of PV modules in parallel(N_{PP}). This product for safety reasons is corrected by a safety factor of 1.25 [13].

$$1.25Icc_{\max} N_{pp} \square I_e$$

(1

4)

As for the inverter, it must be sized so that its nominal power covers the sum of the powers of all users. **Figure 2** shows the configuration of the standalone PV system considered in this study.

4. Economic and Environnemental Analysis

Project Assessment

The economic method applied here is the Life Cycle Cost (LCC). The LCC of a system is the present monetary value of all the acquisition, operation and main- tenance expenses of the system over its lifetime [14]. For our station, these costs also take into account the renewal of used equipment before the lifetime. This is the case of the batteries which are replaced every five years, which suggests 3 ad- ditive lots that will have to be acquired during the life of the project. The present

Figure 2. Proposed design for the PV system.

value (C_{Xn}) of the batch of equipment X of order n acquired after k years is giventaking into account the inflation (i) and depreciation (t) rates as

$$C_{Xn} \square C_X \square \frac{\left(\square 1 \square i \square \square 1 \square t \square \square \right)^k}{\square}$$

(15)

where X designate the equipment and C_X its initial purchase price.

The LCC is then given by the following expression

$$LCC \square C_{GPV} \square C_{bat} \square C_{inv} \square C_{cont} \square C_{op} \square C_{ins}$$

(16)

where

C_{PVG}

is the cost of the PV generator and its accessories.

$C_{inv}, C_{cont}, C_{bat}, C_{op}$

and

C_{ins}

the respective costs of the inverter, regulator, battery, operation and installation.

The LCC reduced to the annual scale (ALCC) is described by

$$\text{ALCC} = \text{LCC} \frac{\left(1+i\right)^{N}}{\left(1-\left(\frac{1}{1+t}\right)\right)} \left(1 - \frac{1}{\left(1+i\right)}\right) \quad (17)$$

We then deduct the present total cost of a kWh by

$$C_{kWh} = \frac{\text{ALCC}}{365 E_{\text{Demand}}}$$

(18)

The Net Present Value (NPV) is the profitability indicator of a project. The investment is profitable if the NPV is positive and unprofitable otherwise. NPV is given by the following equation

$$V = -I_{tot} + \sum^{N}$$

is the initial investment, G_k

the cash flow of year k, N the esti-
mated life of the project and t the depreciation rate of the investment. In our case we will take this rate equal to 10% in agreement with Derbie Gont [15]. As- suming constant revenues and expenses, the cash flow does not vary throughout the uration of the project, we then have

$$\text{NPV} = -I_{tot} + \frac{G_a}{}$$

$$+ K \square N,t\square$$

(20)

where, *G* is the constant value of cash flow and

$$K_a \square N,t\square \quad \square$$

$$\frac{t}{1\square \square 1\square t\square^{\square N}}$$

The updated payback time (*T*) determines when the project becomes profita- ble. It therefore corresponds to the moment where the NPV is zero and is de- duced from the equation

$$\overline{tot} \qquad \qquad \square I \qquad \square \square \frac{T}{i\square 0} \frac{G}{\square 1\square t\square TRA} \quad \square 0$$

(21)

Environmental Analysis

The main indicator of the green nature of a renewable energy installation is the amount of CO_2 avoided. For the autonomous photovoltaic system, this quantity is given by

$$Q_{CO} \quad \square E_p NQ_0 \qquad \qquad _2$$

(2 2)

where, E_p is the energy produced per year, *N* the lifespan of the project (20 years) and Q_0 the greenhouse gas emission factor of the PV generator. This factor varies depending on where the solar equipment is manufactured and also where it is used. The equipment used here is manufactured in China. Thus, the value of Q_0 for Ndziih-Bafou (Cameroon) was evaluated to be 0.094 kg /kWh.

5. Results and Discussion

Recoverable Solar Energy

Figure 3 shows the househo   8
am-10 am and 1 pm-13 pm   e
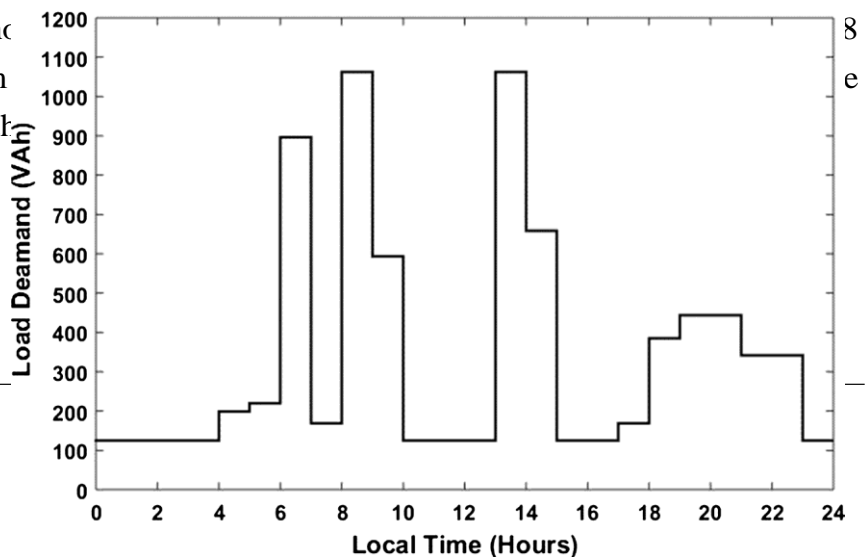is assumed to be constant th

Figure 3. Load profile of the household.

station and must be satisfied regardless of the fact that sunshine is favorable or not at a given period of the year.

This requires an adequate orientation allowing the panels to permanently re- ceive the maximum irradiance. **Figure 4** shows the average monthly availability of daily irradiance at Ndziih-Bafou for panels tilt angle varying from 0 to 90˚.

It can be seen that an optimum angle $\square$ *opt*
for which the incident radiation is

at its peak exists for each month of the year. For five consecutive months, this peak corresponds to a layout of the panels along the horizontal ($\square_{opt} \square 0$). How- ever, the radiation received by the panels during these periods is greater than

that it would receive if the tilt were at a single angle (**Figure 1**). For the other months of the year, there was a significant increase in incident radiation. **Table3** summarizes for each month the optimal tilt angle and the corresponding irra- diance. It also compares the optimized irradiance to that obtained for a fixed tilt. The installation will then be mounted on a frame having a crank allowing ma- nual implementation of the optimal monthly tilt without any additional financial implications. This result contrasts with that of Khaled and Doraid (2012), DerbieGont (2019) who considered a fixed angle all year round.

Sizingthe PV Generator

From the daily consumption (8235.46 VAh) and the solar irradiance data, we
can calculate using (4) the peak power P_p

of the installation.
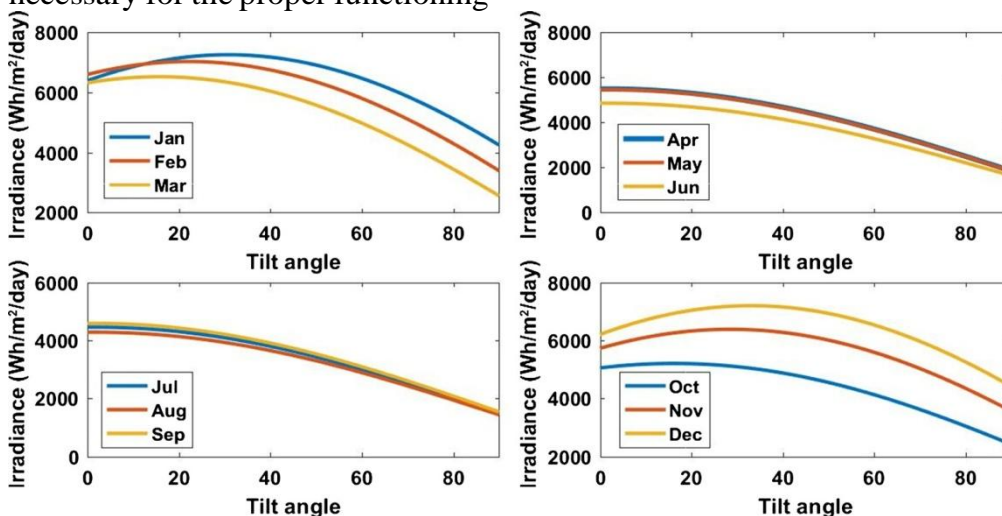
necessary for the proper functioning

Figure 4. Average monthly availability of daily
irradiance at Ndziih-Bafou.

Table 3. Monthly values of the optimal tilt angle as well as the irradiance.

Month	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
βopt (degree)	32	23	17	0	0	0	0	0	3	17	30	34
Optimum Irradiance (kWh/m^2/day)	7.25	7.03	6.52	5.48	5.45	4.85	4.45	4.28	4.58	5.20	6.38	7.19
Irradiance for unique β (kWh/m^2/day)	6.71	6.65	6.49	5.35	5.40	4.72	4.35	4.22	4.58	5.13	5.93	6.51

$$P_p = \frac{8235.46}{4280 \times 0.75}_p \times 1 = 2.56 \,\text{kW}$$

The solar panels are monocrystalline of the type Felicity Solar (310 Wp, 36 V).

According to (5), the number of panels in series is $N_S = \frac{48}{36} = 1.33$

i.e. 2 panels in series.

The number of branches in parallel According to (6) is:

$$N_p = \frac{2.56}{0.31 \times 2} = 4.12$$

i.e. 5 branches in parallel

It comes that the total number of panels to install is $N_T = 10$ panels

The total surface that the panels will occupy is
$A_T = 10 \times 2 = 20 \,\text{m}^2$

To avoid that the panels are too close together, we will increase this total area by de 30% *i.e.* $A_T = 26 \,\text{m}^2$.

Figure 5 presents the energy demand as a function of the PV field production and of the optimized irradiance during the whole year.

It can be seen that the PV field production covers the household energy de- mand all year round. During periods of strong sunshine, this production is well above demand.

Sizing of Battery, Inverter and Regulator

The batteries used are the GEL (150 Ah, 12 V) type. They have an efficiency of 85% and a depth of discharge of 80%. Given the sunshine in the region and the data in **Figure 5**, the autonomy of one day is chosen. So we have

$$C_B = \frac{8235.46 \cdot 1}{0.85 \cdot 0.98 \cdot 0.94 \cdot 0.8 \cdot 48}$$

$= 273.89 \, A \cdot h = 274 \, A \cdot h$

The number B_S of batteries in series according to Equation (11) is $B_S = \frac{48}{12} = 4$.

In parallel we have $B_p = \frac{274}{150} = 1.83 = 2$. The station will finally have 8 batteries in total.

The charge regulator capable of withstanding the short-circuit current of the PV generator while maintaining the voltage of the DC bus is the MPPT type. For
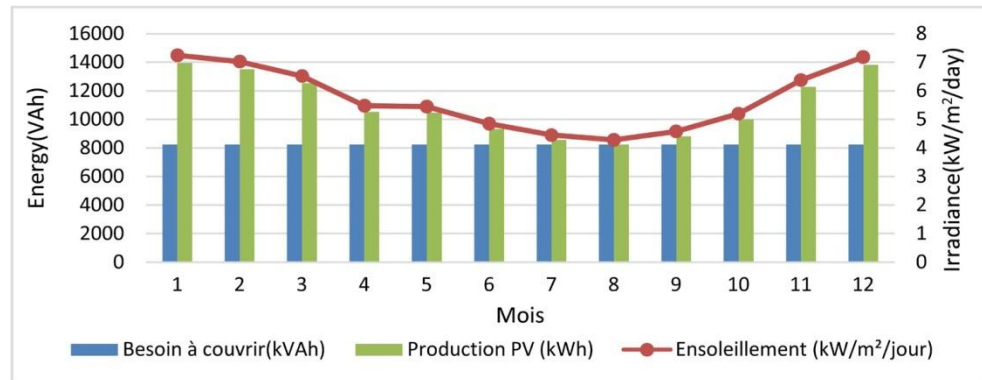

Figure 5. Comparing the Energy demand with the energy generated and the irradiance at Ndziih-Bafou.

this study, we choose the MPPT 60 A/48V regulator with 60 A input current. As for the inverter, the sum of the nominal powers of the charging system is 2800 VA. The input power of the inverter will therefore be equal to 3 kVA (at least) with a DC voltage of 48 V and 50 Hz frequency.

5.4 Economic and Environmental Applications

Table 4 presents the estimated cost of the initial investment. The prices of the equipments are those applied on the local market and expressed in US dollars according to the exchange rate in force on January 1, 2020. The mill which oper-ates 6 days a week, the seventh being devoted

to maintenance, accumulates a to-tal of approximately 313 days of operation per year. It produces 917 $/year, fromwhich the owner takes the manager's salary of 400$/year, as well as the main- tenance costs of the mill and the PV system which amounts to 267 $/year. Thisannual expense (667 $/year) represents 17.24% of the initial investment. Such an approach makes the project more profitable because part of the expenses is covered by the production of the system itself. The equipments will be replaced as follows: Regulators after 8 years, Inverter 11 years and 5 years for the batte- ries. The total energy consumption at constant yearly yield after 20 years is 60,120 kWh.

The LCC of the system for the lifetime of 20 years amounts to $24,495. This value corresponds to an updated total cost per kWh of $0.44. **Figure 6** presents the NPV of the system over its operating time. This graph shows that the project becomes profitable between the 3rd and 4th year. Furthermore, the amount of CO_2 that would be avoided by using the generator over 20 years is 5652 kg.

6. Conclusion

This study dealing with optimal sizing describes both technically and economi- cally the possibility for a household in Ndziih-Bafou to equip itself with a stan- dalone PV station to solve the problem of energy stability. The economic study made it possible to determine the cost of carrying out this project which amountsto $4448 with an updated cost of $0.44 per kWh and a payback period between the 3rd and 4th years. More expensive than the national electricity company which offers a rate of 0.125 $/kWh for monthly consumption less than or equal

Table 4. Estimated cost of initial investment.

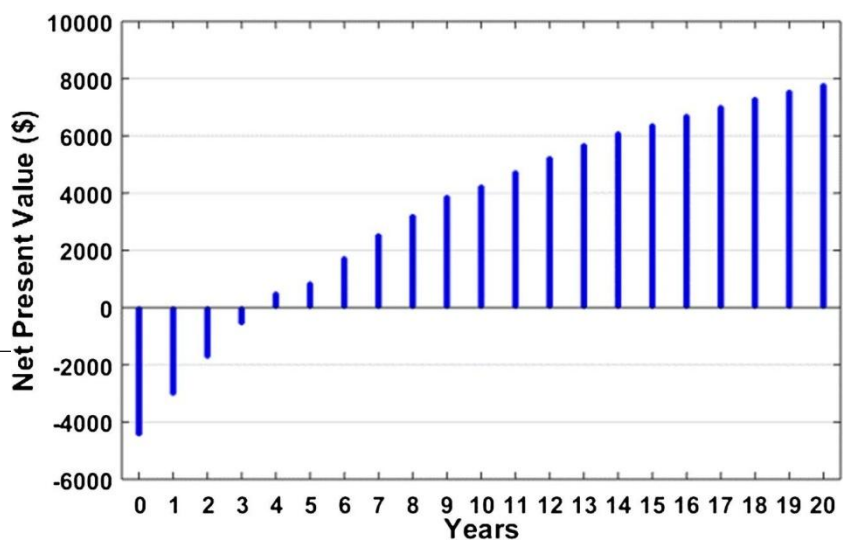| Items	Model	Quantity	Unit Price ($)	Total Price ($)
PV Modules	FL-M-310 (310 Wp; 36 V)	10	160	1600
Batteries	FL-G-150AH12V (150 Ah; 12 V)	8	200	1600
Controller	FL-SCCM-6048 MPPT 60 A/48V	1	254	254
Inverter	FL-IVPL3548-3500VA (3.5 kVA; 48 V)	1	414	414
Labor and accessories	15% of components cost		580	
Total cost of initial investment ($)				**4448**

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Figure 6. NPV of the PV system.

to 110 kWh, this solar generator is quite profitable over the life of the project and offers many advantages such as guarantee of permanent and stable energy and contribution to a cleaner world. The NPV over the lifetime of the system is

$7793. From an environmental standpoint, the result is quite interesting. This autonomous PV system would prevent 5652 kg of CO_2 over 20 years. This study would represent a starting point solution for electrification problem in isolated rural areas in Cameroon and will contribute in the promotion of sustainable de- velopment in rural areas where sunshine is generally favorable for the produc- tion of electricity from solar energy.

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